Changes in the Earth's Rotational Energy Induced by Earthquakes

Benjamin Fong Chao

Geodynamics Branch, NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

Richard S, Gross

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109

Abstract The kinetic energy of the Earth's rotation can be separated into two parts: the spin energy and the polar motion energy. Here we derive rigorous formulae for their changes, where the polar-motion energy change is related to the polar-motion excitation function via a treatment of reference frames. The formulae are then applied to compute co-seismic energy changes induced by the static displacement field produced in an idealized Earth model by a total of 11,015 major earthquakes that occurred during 1977-1993. An extremely strong statistics is found in the earthquakes' tendency in increasing the Earth's spin energy; the rate during 1977-1993 was +6.7 GW, about the same as the total seismic wave energy release, The corresponding polar-motion energy changes are 10^{-6} times smaller and had no detectable statistical tendency in their signs.

1. Introduction

Mass redistributions of material in or on the Earth will produce two independent global geodynamic effects. 11 will change the Earth's rotation via the conservation of angular momentum. It will also change the Earth's gravitational field according to Newton's gravitational law. An earthquake faulting generates such la[:,c-scale static displacement field in the Earth; so the Earth's rotation and gravitational field, as well as their associated energy, will change as a result. Chao & Gross (19S7) have formulated and computed earthquake-induced changes in the Earth's rotation and low-degree gravitational field. The present paper focuses on the corresponding change in the rotational energy, while a companion paper (Chao et al. 1994) treats the changes in the gravitational energy.

Munk & MacDonald (1960) have show that, to first order approximation, validations of the EarLb's rotation vector as seen in the terrestrial reference frame can be separated dynamically into spin variation and polar motion. We shall derive formulae for the rotational kinetic energy change from first principles in parallel to their linearization scheme. It will be shown that the rotational *energy* change can as well be separated, to first order, into spin energy change and polar motion energy change. It should be mentioned that the first-order expression for spin energy change can be derived alternatively in a straightforward manner from the conseri l'alien of the axial component of angular momentum (cf. Dahlen 1 977; see also equation 5 below). By the same token, the change in the polar-motion energy can be derived from the expression for the total polar-motion energy for an elastic Earth, which is for really equivalent to that associated with the Eulerian motion of a rigid body (e.g., Landau & Lifshitz 1 976). However, as we will sex, careful interpretation of the associated reference frame is necessary.

Chao & Gross (19S'/) computed for ?.146 major earthquakes that occurred during 1 977- 1985 and found strong non-random behavior of earthquakes in producing co-seismic rotational and gravitational changes, in particular, they found that earthquakes have an ext I emely strong tendency to speed up the Earth's spin, albeit slightly. This happens becasue the earthquakes tend to move mass toward the rotation axis, just as drawing the arms dose.] to the body would speed up a skater's spin. The spin energy will increase in the process because work is done againt the centrifugal force. In this paper we apply the rotation energy formulae to the co-seismic mass redistribution associated with the earthquake-induced static displacement field in the Earth. We compute both spin energy and polar-motion energy changes caused by 11,015 major earthquakes that have occurred during January 1, 1977 to July 31, 1993. In parallel to Chao & Gross (1987) and Chao et al, (1 994), we examine the magnitude and statistics of these rotational energy changes.

2. General Formulation

Consider a rotating Earth model for which some terrestrial (body) reference frame is defined. We fix the origin of the coordinate system at the center of mass. 'J he Cartesian x, y and z coordinate axes are oriented along the 0° (Greenwich) Meridian, the 90°E Meridian, and the Earth's mean rotation axis, respectively. The choice of this z axis defines the zero polar motion energy which corresponds to zero wobbling motion. The instantaneous rotation velocity vector can be written as

$$\Omega = \Omega\,[\, m_1 \hat{x} + m_2 \hat{y} + (1+m_3)\hat{z} \,] \tag{1}$$

where ^ denotes unit vector, $\Omega = 7.2921\times10^{-5}$ s"ʼ is the mean (sidereal) rotation rate of the Earth, and m_i are small dimensionless perturbations, m_3 describing variations in the spin and m_1, m_2 describing polar motion. To first order in m_i, the centrifugal potential generated by Ω at location **r** in the Earth is (e.g., Wahr 1985):

$$U(\mathbf{r}) = \tfrac{1}{2}\,[\,/“?/s212 - (\mathbf{r}\cdot\Omega)^2\,]$$
$$= \tfrac{1}{2}\,\Omega^2\,[\,(x^2+y^2)\;(1 + 2m_3)\;2m_1\,xz\;2m_2\,yz\,] \tag{2}$$

The centrifugal acceleration is given by $\nabla U(\mathbf{r})$.

Suppose an infinitesimal displacement field $\mathbf{u}(\mathbf{r})$ is produced in the otherwise unperturbed Earth. This displacement dots mechanical work against the centrifugal force; and the relational energy change is equal to this work integrated over the volume of the Earth:

$$\Delta E = -\int \rho\,(\mathrm{I}")\;\mathbf{u}(\mathbf{r})\cdot\nabla\;u(\mathrm{r})\;dV \tag{3}$$

where $\rho(\mathbf{r})$ is the Earth's density distribution. The position vector **r** of a material particle refers to a 1 agrangian (as oppose.d to Eulerian) description which, under the conservation of mass, allows volume integration to be carried out over the undeformed body.

Combining equations (2) and (3), one gets

$$\Delta E = -\tfrac{1}{2}\,\Omega^2\,[\,(1+2m_3)\int \rho(\mathbf{r})\mathbf{u}(\mathbf{r})\cdot\nabla(x^2+y^2)\,dV$$

$$+\,2m_1\int \rho(\mathbf{r})\mathbf{u}(\mathbf{r})\cdot\nabla(-xz)\,dV + 2m_2\int \rho(\mathbf{r})\mathbf{u}(\mathbf{r})\cdot\nabla(-yz)\,dV\,] \tag{4}$$

valid to first order in $\mathbf{u}$. The first term in the bracket gives the change in the spin energy, ΔE_s, whereas the remaining two terms give the change in the polar motion energy, ΔE_{pm}. To first order in m and $\mathbf{u}$, they separate in a natural and convenient manner.

The energy changes can be simplified, at least conceptually, as follows. Let C be the polar moment of inertia of the Earth about the z axis: $C = \int \rho(\mathbf{r})(x^2+y^2)dV = 8.0378\times 10^{37}$ kg m^2. Then the first integral in (4) is precisely the change in C, c_{33}, due to the displacement $\mathbf{u}(\mathbf{r})$ in the Lagrangian description. Thus, to first order in $\mathbf{u}$,

$$\Delta E_s = -\tfrac{1}{2}\,\Omega^2\,c_{33} \tag{5}$$

where a term proportional to $|m_3| \ll 1$ has been neglected in the presence of 1.

By the same token, the remaining two integrals in (4) are recognized as the Lagrangian description of the changes in the xz and the yz components of the inertia tensor ($-\int \rho xz dV$ and $-\int \rho yz dV$, respectively). Denote these changes as c_{13} and c_{23}, then

$$\Delta E_{pm} = -\,\Omega^2\,\mathbf{m}\cdot\mathbf{c} \tag{6}$$

where for brevity we have written $\mathbf{m} = (m_1, m_2)$, and $\mathbf{c} = (c_{13}, c_{23})$ as 2-dimensional vectors. Here $\mathbf{m}$ is expressed in radians; typically $|\mathbf{m}| \sim 10^{-6}$ from observation (see Fig. 1).

The quantities c_{33}, c_{13} and c_{23} are usually computed for geophysical processes with no regard to any induced rotational deformation of the (elastic) Earth. In reality, the extra centrifugal force arising from the rotational change itself can cause an extra change in the above parameters, the amount of which depends on the Earth's elastic properties. Numerically, however, this contribution can be neglected because its relative magnitude is only on the order of 10^{-3}, as shown by Munk & MacDonald (1960, eq. 6.1.8).

It is instructive to derive the total polar-motion kinetic energy from equation (6). This can be done in terms of the polar-motion excitation function due to a mass redistribution computed with respect to the Tesserand's frame, $\Psi = k_w\mathbf{c}/(C - A)$, where $k_w = 1.43$ is the polar-motion transfer function (Munk & MacDonald 1960), and A = 8.0115 $\times 10^{37}$ kg m? is the Earth's equatorial moment of inertia. Hence,

$$A 1<,))), \cdot \; \Omega^2 (C-A)\, \mathbf{m}\cdot\Psi' \,/\, k_w \tag{7}$$

Following the argument of Chao (1 984, equations 13- 1 5), it can be shown that the instantaneous change in the polar motion causal by Y' is

$$\Delta\mathbf{m} = -k_w\,(C/A)\,\Psi' \tag{8}$$

Substituting equations (7,8) into (6) leads readily to the expression for the total polar-motion energy

$$E_{pm} = \tfrac{1}{2}\,\Omega^2\,[A\,(C-A)/C]\,\mathbf{m}\cdot\mathbf{m} \tag{9}$$

This equation is formally identical to the well-known expression for the kinetic energy of the Eulerian wobble of a rigid body.

The same effect associated with the minus sign in equation (8) explains the minus sign in equation (7). E_{pm} increases if Y' opposes m in direction: As viewed in the terrestrial frame, the center of the new m moves away from the original $\mathbf{m}$, increasing $|\mathbf{m}|$ and hence E_{pm}. The reverse is true if Y' is parallel to $\mathbf{m}$. E_{pm} remains unchanged if Y' is normal to $\mathbf{m}$.

A word of caution is in order here with respect to the definition of $\mathbf{m}$. As described above, our formula applies to the location of the Notational pole relative to the 'mean pole" , which in turn is our reference level corresponding to zero polar-motion energy. Two complications arise as a result. First, the "reported" pole position measurement is the location of the celestial ephemeris pole, rather than the rotation pole (Gross 1 992). The dynamic difference is proportional to the time derivative of the excitation Y'. Chao (1 984) has shown that, for an abrupt displacement such as an earthwuake faulting, the difference is numerically negligible on the order of the Earth's oblateness (- 1/300), in fad, the excitation Ψ' given above neglects the time derivative terms for the same reason. The second complication is a more obvious one. That is, the pole position is normally given relative not to the mean pole but to the Conventional North Pole, which is defined to be the mean pole for the period

1900- 1905. The North Pole no longer coincides with the present mean pole as a result of a secular drift over the years. Hence an empirical secular shift of the origin needs to be invoked in the polar-motion series to be free from the polar drift as much as possible, so that only the "wobbling" motion remains. This will be done below. Note that our definition of **m** thus gives scalar quantity equation (9) an invariant, positive-definite form with respect to coordinate transformation as it should.

We now apply the theory to co-seismic, static displacement in the Earth produced by an abrupt, step-function earthquake faulting. Following Chao & Gross (1987) and using the normal mode theory (Gilbert 1970), this displacement can be expressed as an infinite sum of the Earth's free oscillation normal modes:

$$\mathbf{u}(\mathbf{r}) = \sum_k \omega_k^{-2}\, \mathbf{u}_k(\mathbf{r})\ \mathbf{M} : \mathbf{E}_k^*(\mathbf{r}_f), \quad t>0 \tag{10}$$

The asterisk denotes complex conjugation, $\mathbf{u}_k(\mathbf{r})$ is the eigenfunction of the kth mode normalized such that $\int \rho\, \mathbf{u}_k^* \cdot \mathbf{u}_k\, dV = 1$; ω_k and $\mathbf{E}_k = \frac{1}{2}[\nabla \mathbf{u}_k + (\nabla \mathbf{u}_k)^T]$ (where superscript T denotes transpose) are the corresponding eigenfrequency and elastic strain tensor, respectively; $\mathbf{r}_f$ and $\mathbf{M}$ are the focus and the seismic moment tensor of the earthquake, respectively. The global spatial scale and the long temporal scale under consideration allow the simplified representation of an earthquake as a point source with a step-function time history. $\mathbf{M}$ is symmetric owing to the indigenous nature of the earthquake which exerts zero net torque. The advantage of using normal mode theory has been pointed out by Chao & Gross (1987): Since the eigenfunctions already account for the elastic and gravitational forces as well as the physical boundaries in the Earth, none of these complications need be taken into explicit consideration. Furthermore, the formulation is particularly efficient in computation (see below).

To evaluate $\mathbf{u}(\mathbf{r})$, we consider a simple Earth model which is a spherically symmetric, non-rotating, elastic and isotropic approximation of the real Earth (so-called SNREI Earth model). Since the Earth's deviation from spherical symmetry is relatively small (the rotation and the ellipticity, by far the largest deviations, are only of the order 1/300), the error committed in using an SNREI representation is negligible to this order.

The density distribution is then a function of radial distance only: $\rho(\mathbf{r}) = \rho(r)$. The normal modes $\mathbf{u}_k$ of an SNREI Earth are of two kinds -- spheroidal and toroidal. The toroidal modes, being divergence-free, have zero first-order effect on the mass density; so they drop out of the modal sum

(10). The spheroidal modes can be written as

$$\mathbf{u}_{nlm}(\mathbf{r}) = \hat{\mathbf{r}}\, U_{nl}(r)\, Y_{lm}(\theta, \lambda) + V_{nl}(r)\, \nabla_1 Y_{lm}(\theta, \lambda) \tag{11}$$

where n, l, m are respectively the overtone number, degree and order of the normal modes (n, l = 0,1, 2,..., m = $-l$,...,l). U_{nl} and V_{nl} are the radial eigenfunctions; Y_{lm} are the fully normalized, complex surface harmonic functions of latitude θ and longitude λ; and ∇_1 is the surface gradient operator $\hat{\theta}\partial_\theta + \hat{\lambda}\sec\theta\partial_\lambda$. The eigenfrequencies of the (n, l)th (spheroidal) multiplet will be denoted by ω_{nl}. The eigenelements are functionals of the interior structure of the Earth, and independent of m under the assumed spherical symmetry.

The task now is to substitute equation (11) into (10) and then use it to calculate c_{33} and c. The detail of this procedure has been presented by Chao & Gross (198"~). Substituting that result into equations (5) and (6) yields

$$\Delta E_s = \Omega^2\, \mathbf{M} : \textstyle\sum_n [\, G_n\, \mathbf{E}_{n00}(\mathbf{r}_f) + F_n\, \mathbf{E}_{n20}(\mathbf{r}_f)\,] \tag{12}$$

$$\Delta E_{pm} = -(\sqrt{6}\,\Omega^2)\, \mathbf{m} \cdot [\, \mathbf{M} : \textstyle\sum_n F_n \langle \mathrm{Re}\,\mathbf{E}_{n21}(\mathbf{r}_f), \mathrm{Im}\,\mathbf{E}_{n21}(\mathbf{r}_f) \rangle\,] \tag{13}$$

where the summations are carried out over the infinite set of spheroidal overtones. F_n and G_n are the following functionals of the SNREI Earth model:

$$F_n = (4\sqrt{\pi}/3\sqrt{5})\, \omega_{n2}^{-2} \int_0^a \rho(r)\, r^3\, [\, U_{n2}(r) + 3\, V_{n2}(r)\,]\, dr \tag{14}$$

$$G_n = -(4\sqrt{\pi}/3)\, \omega_{n0}^{-2} \int_0^a \rho(r)\, r^3\, U_{n0}(r)\, dr \tag{15}$$

Only the spheroidal overtones with $l = 0$ or ($l = 2$, $m = 0$) contribute to ΔE_s, while only the spheroidal overtones with $l = 2$ and $m = 1$ contribute to ΔE_{pm}.

3. Data

Following Chao & Gross (1987), we adopt the 1066B Earth Model of Gilbert & Dziewonski (1975) for the SNREI Earth parameters and normal mode eigenelements. For the earthquake moment tensors M we use the centroid-moment tensor solutions published in the Harvard catalog (e.g., Dziewonski et al. 1993), which consists of 11,015 earthquakes that occurred during 1977/1/1 to

] 993/'//3] with body-wave magnitude larger than about 5. In terms of energy release one need only consider the major earthquakes. Smaller earthquakes, although numerous, involve relatively little energy and can be ignored completely.

Pole position m is also needed to compute ΔE_{pm}. We choose to use the "Space93" time series (Gross 1 994). The series consists of daily pole determinations from a Ktilman-filter combination of all independent space geodetic observations. The same time span as the earthquake wits is taken. As explained above, the polar offset and secular drift need be removed from the polar motion data in an optimal fashion, so as to move the origin for m to the mean pole. We accomplish this by least-squares fitting a linear combination of an annual term, a Chandler term, plus a second-dcyce polynomial to each of the x and y components of the pole position The polynomial (which turned out to be rather linear) is then subtracted. The resultant pole path of m during 197"//1 /1 1 993/7/3 1 is displayed in Figure 1.

4. Results and Discussion

We then compute ΔE_s using equation (12) and ΔE_{pm} using (1 3). The convergence of the summation was found to be quite rapid, usually with the value of ΔE_g obtained after summing only two overtone modes being well within 1‰ of its final value, although we actually summed over 26 overtone modes having periods longer than 45 s. The results arc shown in Figure 2. The cumulative energy changes arc given in Figure 3.

In computing ΔE_{pm}, the interim (but physically meaningful) parameter of the seismic excitation function Ψ' is obtained. The cumulative series for Y' in terms of its x- and y- components are presented in Figure 4. The linear trend found by Chao & Gross (1 987) for 19"/7- 985 becomes weaker here with the additional data in the years past 1985.

For the purpose of illustration, we single out in Table 1 the results for he following seven largest earthquakes in recent decades (with seismic moment M_0 exceeding 10^{21} N m):

Event 1:	May 22, 1960, Chile
Event 11:	March 28, 1964, Alaska, USA
Event 111:	August 19, 1977, Sumba, Indonesia
Event IV:	March 3, 1985, Chile
Event v:	September 19, 1985, Mexico
Event VI:	May 23, 1989, Macquarie Ridge

Event VII: June 9, 1994, Bolivia

The source mechanism of Events I and II, which occurred before the span of the Harvard catalog, are taken from Kanamori & Cipar (1974) and Kanamori (1970), respectively. The pole position m at the time of these two events (needed to compute ΔE_{pm}) are taken from the International Latitude Service data: (- 154 mas, 42 mas) and (- 194 mas, 171 mas), after removal of an offset and long-term drift similarly as above. Event VII in 1994 is also outside our studied period. It is a deep-focused event and has the largest seismic moment since Event III in 1977. Its seismic moment tensor solution (adopted from the preliminary Harvard catalog) is considered preliminary at this writing. The corresponding pole position is also preliminary: (126 mas, 64 mas) after detrending (C. Ma, personal communication, 1994). The seismic wave energy E_w is computed according to the empirical relation (Kanamori 1977): $E_w = M_0/(2\times10^4)$ (see also Chao et al. 1994).

We shall now study the statistics of the rotational energy changes. We do so by examining the χ^2 statistics of the sign of the ΔE_s and ΔE_{pm} values. ΔE_s is proportional to c_{33} which in turn is proportional to the change in the length-of-day, ΔLOD. Hence it has the same χ^2 statistics as ΔLOD which has been calculated in Chao et al. (1994). There are much more positive ΔE_s values than negative ones: Out of the 11,015 events, the difference is as many as 12?'/3, much greater than $\sqrt{11,015}=105$ expected from a binomial distribution for random fluctuation, implying an extremely low probability that this phenomenon is due purely to random fluctuations. in other words, earthquakes produce positive ΔE_s much more readily than negative ΔE_s, as is clearly evident in Figure 2(a) and the increasing trend in 3(a). The corresponding χ^2 is as high as 147 (far higher than, say, the critical values of 6.64 at 10/0 significant level or 10.8 at 0.1% significant level). Physically it indicates that the earthquake mechanisms are such that the resultant seismic displacement tends to act against the spin centrifugal force. Thus, earthquakes have a strong tendency to decrease the Earth's greatest moment of inertia C, causing a faster spin and increasing the spin energy in the process. The situation is analogous to a spinning skater gaining spin energy by all-awing the arms closer to the body against the centrifugal force while the angular momentum stays constant. From Figure 3(a), the average rate of ΔE_s increase is rather steady at about 2.1×10^{17} J yr^{-1}, or 6.7 gigawatt (GW or 10^9W), during 1977-1993.

in contrast, earthquakes show no preference one way or the other in the sign of the polar-motion energy change, and no statistical tendency is detectable. The number of negative signs of the ΔE_{pm} values is larger than the number of positive signs by a mere 69, within that expected from random fluctuations. The χ^2 of this particular realization is only 0.43, corresponding to a significant level of ~ 50%. This non-trending nature of ΔE_{pm} gives Figure 3(b) the characteristic of a random walk process. From Figure 3(b), the overall fluctuation in ΔE_{pm} during *1977-1993* is on the order of 10^{12} J, or only=+ 10^{-6} GW. The overall size of ΔE_{pm} *is* thus six orders of magnitude smaller than ΔE_s. The reason is the following: assuming that $|c|$ and $|c_{33}|$ produced by earthquakes arc comparable in size, equations (5) and (6) lead to $\Delta E_{pm}/\Delta E_s \sim |m|$, which is of the order 10^{-6}.

We can now compare the rate of some relevant geophysical energy changes (for reference, the total human power consumption is about 104 GW.):

Total heat flow	4×10^4 GW
Spindown caused by tidal braking	3×10^3 GW
Earthquake-induced gravitational, 1977-93	~ 2.0×103 GW (Chao et al, 1994)
Mantle convection	1×10^3 GW
Total seismic wave, 1977-93	4.7 GW (Chao et al. 1994)
Earthquake-induced spin, 1977-93	+6.7 GW (This study)
Earthquake-induced polar motion, 1977-93	± 10^{-6} GW (This study)

We see that in general the earthquake-induced rotational energy changes are relatively small in terms of the global energetics. At +6,7 GW, the steady increase of ΔE_s with time due to earthquakes is totally overwhelmed by the tidal braking in the Earth's spin, which amounts to a secular decrease in ΔE_s at a rate of about -3×103 GW. However, so far as the seismic energetics is concerned, ΔE_s is not trivial: its magnitude is comparable to, and usually greater than, the total seismic wave energy release by earthquakes (also cf. Table 1). ΔE_{pm}, being six orders of magnitude smaller than ΔE_s, is completely negligible.

What is the energy source for positive ΔE_s and the sink for negative ΔE_s (and for that matter, the source and sink for ΔE_{pm})? As a mechanism of the plate tectonic movement, earthquakes arc a surface manifestation of the mantle convection. The power required for the latter is about 103 GW (e.g., Stacey 1977), representing a much larger energy reservoir for ΔE_s (and ΔE_{pm}). Chao et al. (1994; cf. also Dahlen 1977) have demonstrated that, besides operating its own energy budget and changing the rotational energy, an earthquake induces a co-seismic gravitational energy change ΔE_g that is two to three orders of magnitude larger. Figure 5 shows the cumulative ΔE_g adopted from

Chao et al. (1994), While ΔE_s steadily increases, there is a similar anti equally strong tendency for the earthquakes to reduce the gravitational energy ΔE_g. ΔE_g is generally a few hundred times larger than ΔE_s with the opposite sign (a positive ΔE_g is almost always associated with a negative ΔE_s, and vise versa). The reason is simply that the gravitational force in the Earth is a few hundred times larger than the centrifugal force and generally points in an opposite direction to the centrifugal force. It is conceivable that this ΔE_g can easily serve as a source and sink for ΔE_s (and ΔE_{pm}) in the grand scheme of plate tectonics, Under this scenario, the dominant energetic effect of an earthquake is the transfer of the gravitational energy from and into other forms of energy. The accompanying change in the rotational energy is a secondary effect, but the physical mechanism for the energy transfer remains to be studied.

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Table 1. Changes in spin energy (ΔE_s) and polar-motion energy (ΔE_{pm}), compared with seismic wave energy E_w, induced by seven great earthquakes.

Event	I	II	III	IV	V	VI	VII
(M_0, 10^{21} N m)	(270)	(75)	(3.6)	(1.0)	(1.1)	(1.4)	(3.0)
E_w (10^{18} J)	J3.5	3.8	0.18	0,050	0.0s5	0.070	0.15
ΔE_s (10^{18} J)	18.4	-14.9	-0.72	0.22	0.20	0.13	0.51
ΔE_{pm} (10^{12} J)	-37.9	-28.9	0.70	- 0,s3	-0.18	0.?9	0,1'1

Figure Captions

Figure 1. The polar motion path with reference to the mean pole, during 1977- 1993 (an offset and a trend removed from the observed path). The x axis is along the Greenwich Meridian, the y axis along the 90°E longitude. The conventional North Pole is labeled N for reference. 1 milliarcsecond = 4.848×10^{-9} radian.

Figure 2. (a) Spin energy change ΔE_s, and (b) polar-mot ion energy change ΔE_{pm}, induced by 11,1215 major earthquakes during 197'7- 1993.

Figure 3. Same as Figure 2, but for the cumulative' energy changes.

Figure 4. x and y components of the cumulative excitation of polar motion due to 11,015 major earthquakes that occurred during 1977-1993.

Figure 5. Cumulative gravitational energy change in the Earth induced by 11,015 major earthquakes that occurred during 1977-1993 (adopted from Chao et al.1 994).

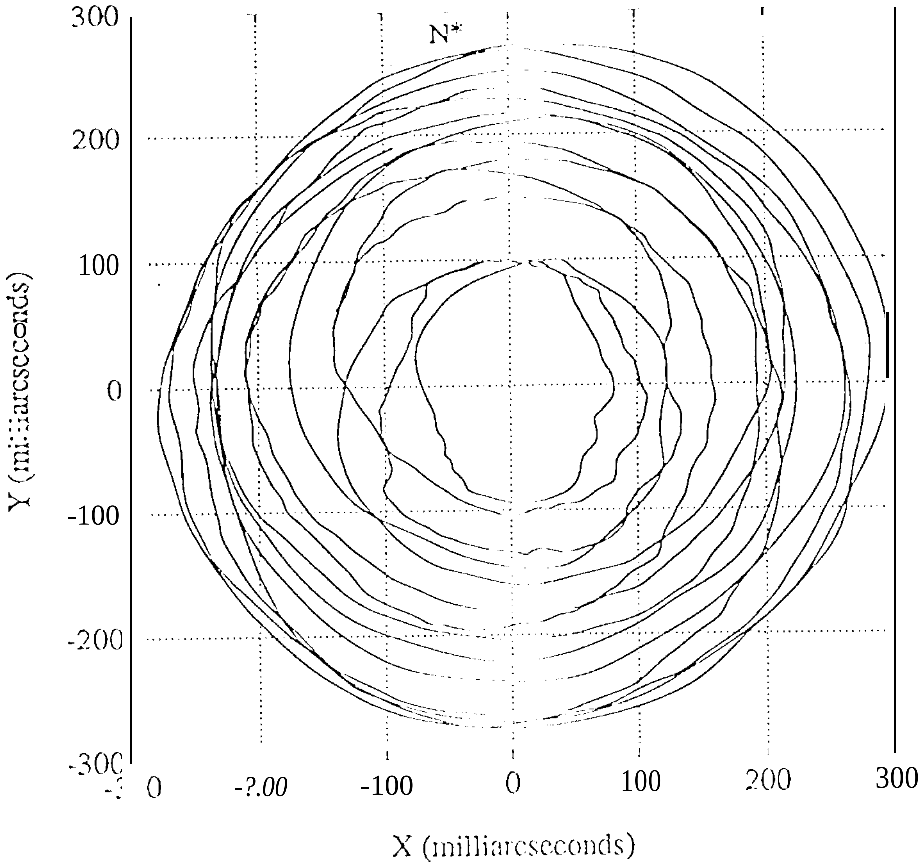
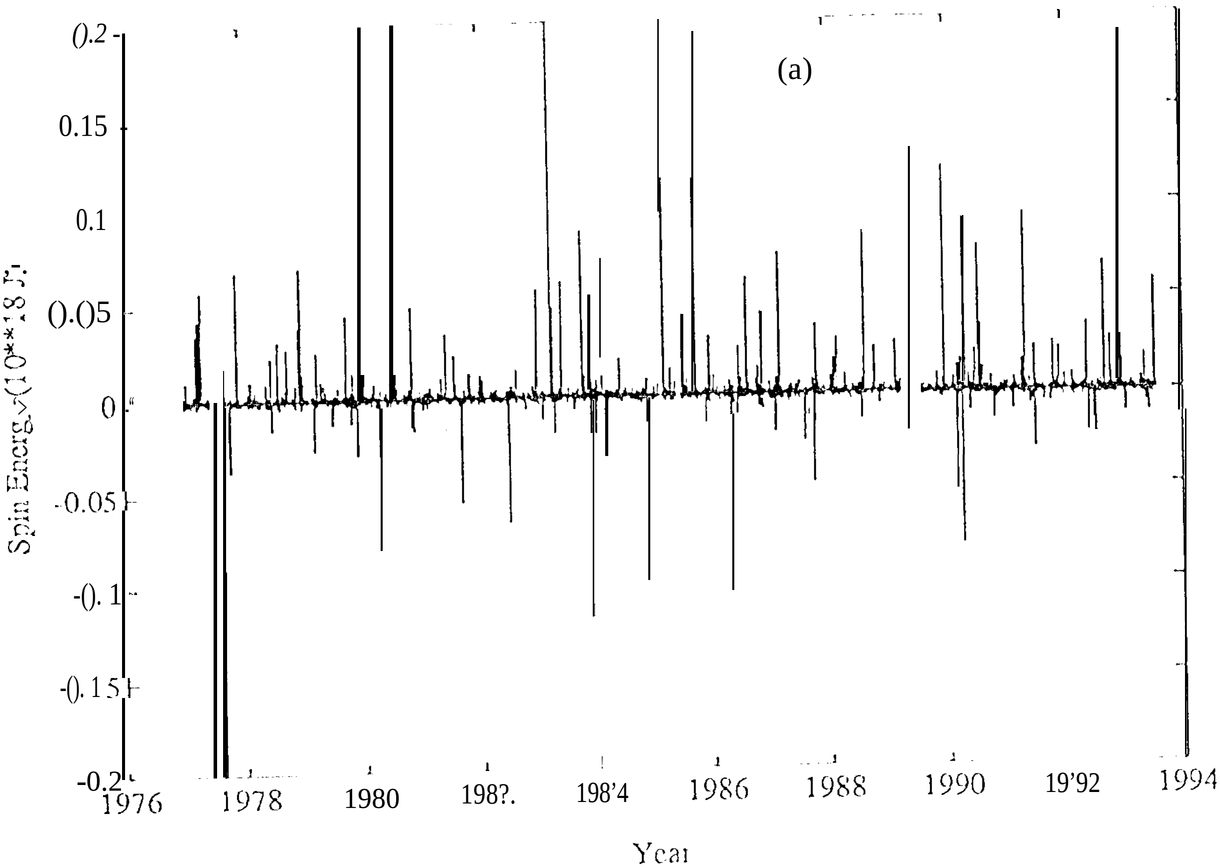

N*
300
200
100
0
-100
-200
-300
Y (milliarcseconds)
-300
-200
-100
0
100
200
300
X (milliarcseconds)

Fig 1


(a)
Spin Energy (10**18 J)
Year
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994

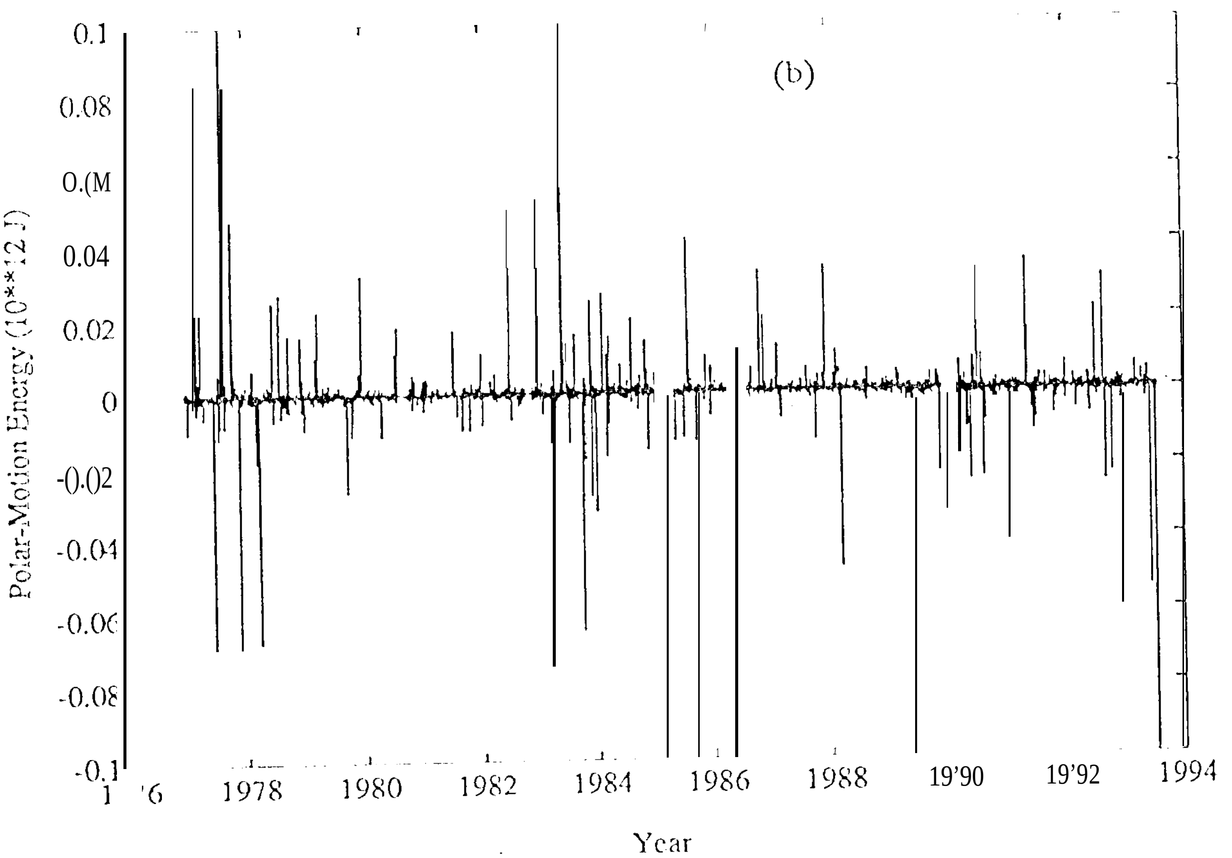
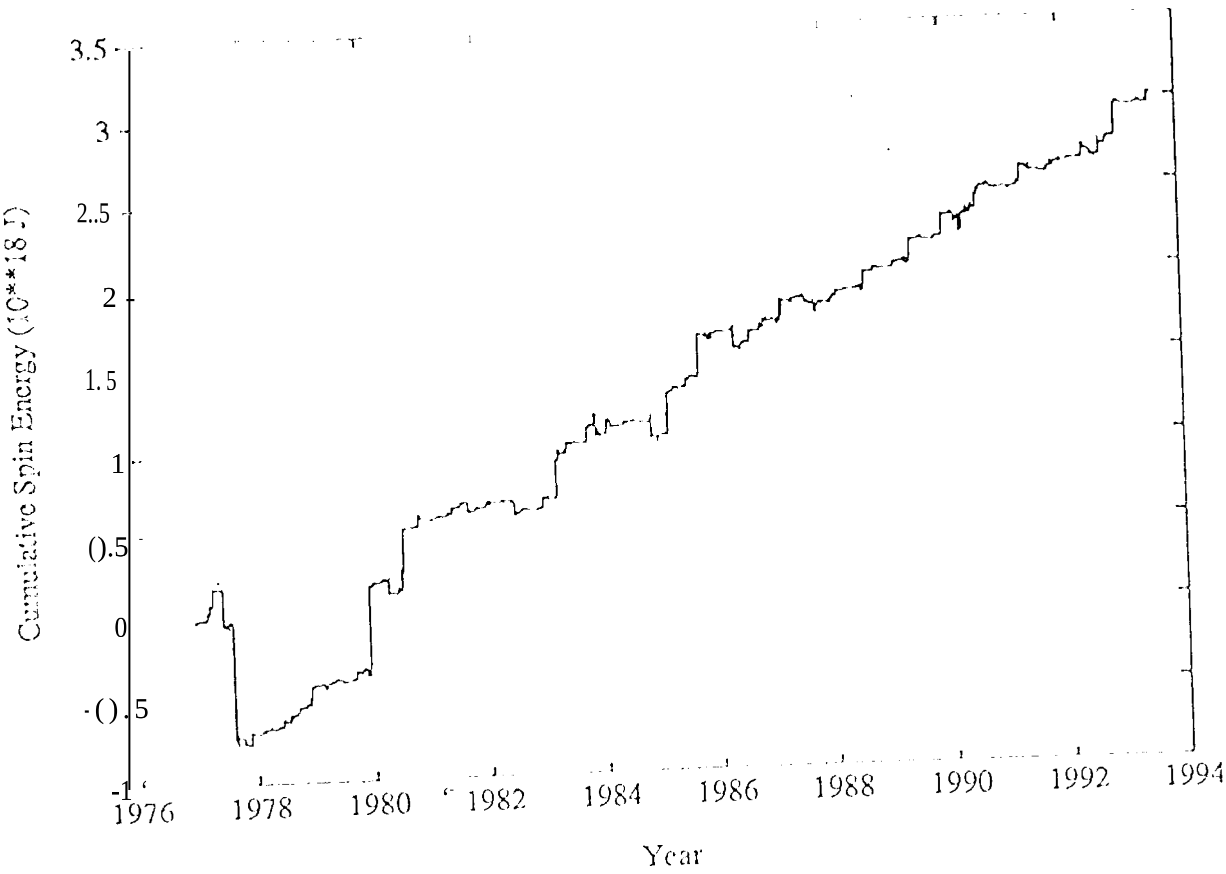

(b)
Polar-Motion Energy (10**12 J)
Year
0.1
0.08
0.04
0.02
0
-0.02
-0.04
-0.08
-0.1
1978
1980
1982
1984
1986
1988
1990
1992
1994

Fig 2


Cumulative Spin Energy (10**18 J)
Year
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994

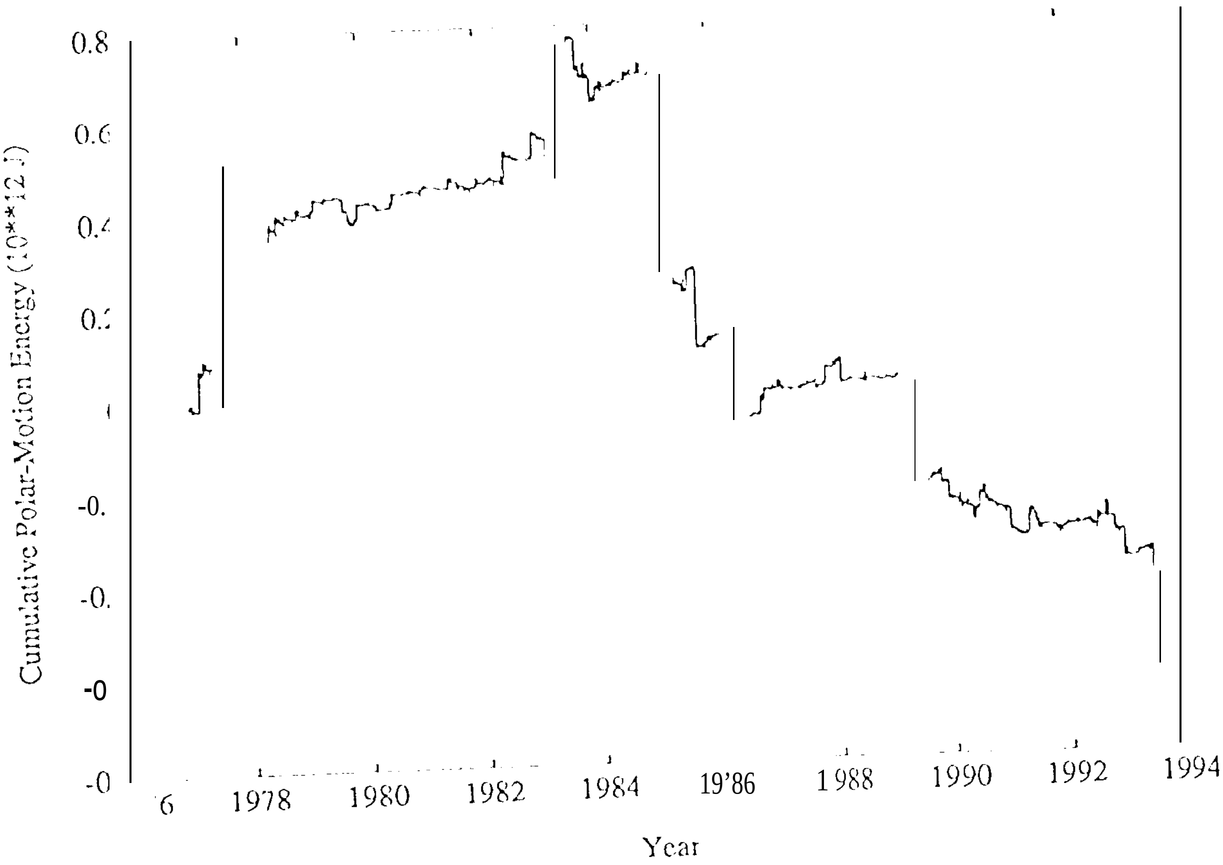

Cumulative Polar-Motion Energy (10**12 J)
Year
1978
1980
1982
1984
19'86
1988
1990
1992
1994

Fig 3

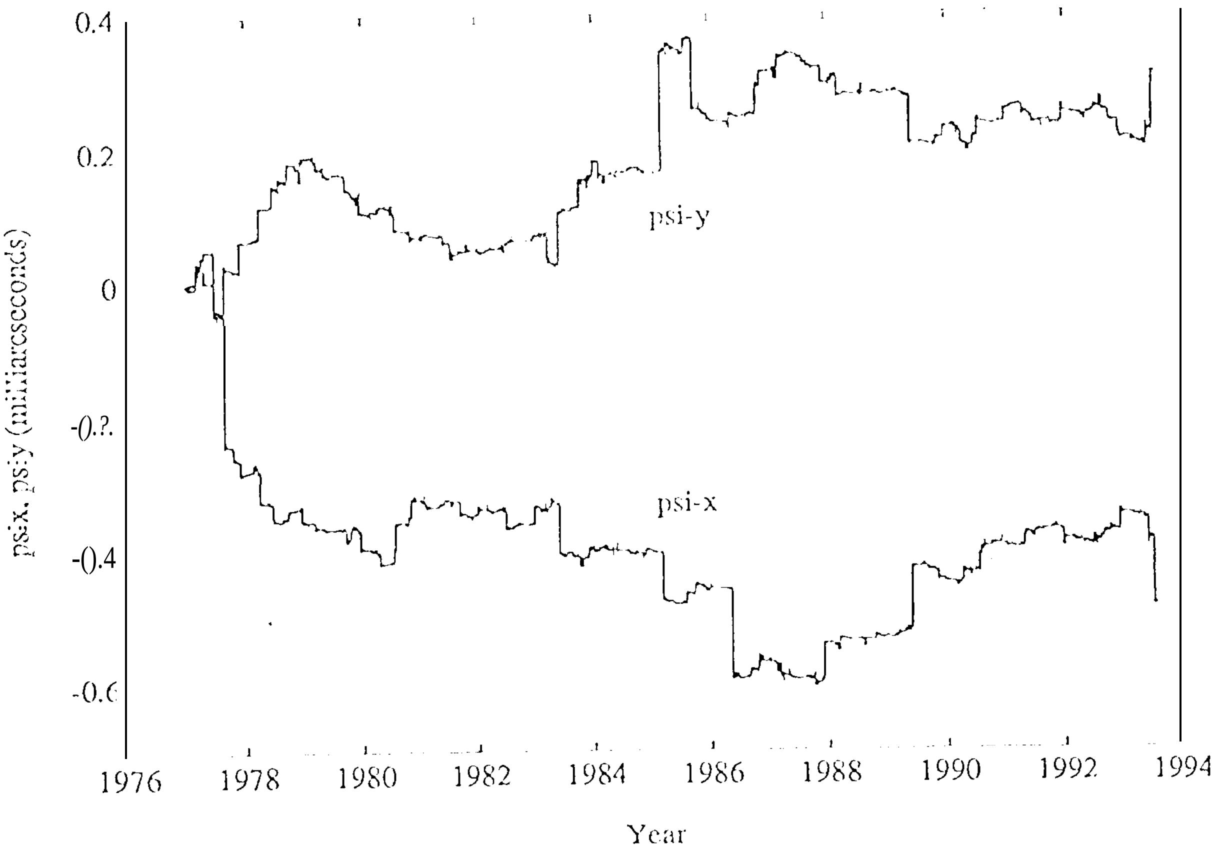

0.4
0.2
0
-0.2
-0.4
-0.6
psi-x, psi-y (milliarcseconds)
psi-y
psi-x
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
Year

Fig 1

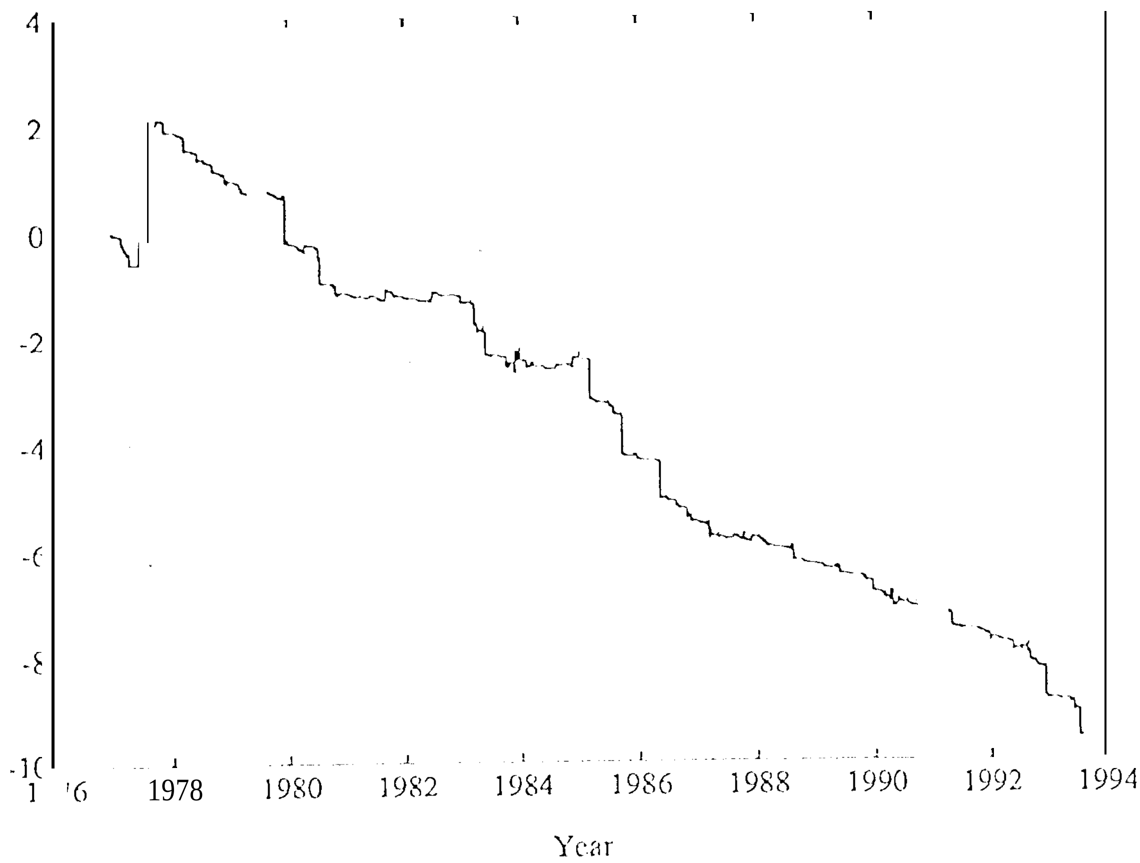

4
2
0
-2
-4
-6
-8
-10
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
Year

Fig 5